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Development of a Conceptual Design Mission Analysis System for Guided Entry Systems

DFY07 Year-End Report / DFY08 Technical Plan
University IR&D Project

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DESCRIPTION OF PROJECT

The DFY07 UIR&D effort focused on identifying relevant technologies for achieving pinpoint accuracy (<100 m) for Mars landing applications. System performance was evaluated for a Mars Science Laboratory (MSL) baseline mission architecture with use of CSDL's EDL simulator. Probabilistic assessments were performed on the effects of hypersonic guidance accuracy, guided subsonic aerodynamic decelerators, and propulsive terminal descent algorithms. Additionally, research was performed on an innovative EDL architecture—ballistic entry augmented with a Smart Divert capability to sites that are defined as safe *a priori* from orbital reconnaissance or other means. In addition to these system trades and assessments, improvements were made to the CSDL EDL simulation capability.

The DFY08 UIR&D effort extends the DFY07 pinpoint landing technology identification task into an integrated, multidisciplinary analysis framework for guided, atmospheric entry vehicles in conceptual design phase. This framework will have the capability to estimate the performance and mass of a user-defined hypersonic vehicle using vehicle geometry, hypersonic aerodynamics, flight mechanics, guidance, navigation, and control (GNC), thermal response, and mass estimation models. The basis of the framework is a tool presently under development within the Space Systems Design Laboratory (SSDL) at the Georgia Institute of Technology. The framework currently supports unguided, lifting blunt-body entry and aerocapture systems at Earth and Mars[1]. The focus of this project is to: (1) replace the first-order trajectory simulation in the present version of this tool with the CSDL simulation developed in the DFY07, and (2) add a GNC capability to this framework for hypersonic aeromaneuvering, subsonic aerodynamic decelerator descent, and propulsive terminal descent such that the framework would be broadly applicable to:

1. Entry, descent, and landing
2. Aerocapture
3. Precision and/or pinpoint landing
4. Mars and Earth robotic missions

In addition to providing CSDL a framework for rapid entry vehicle analysis, this research will continue quantification of the enabling technologies for pinpoint landing (landed footprints of less than 100 m) by utilizing this improved analysis framework for this assessment. Two test applications – an Orion-like skipping entry upon return from the moon and a future Mars robotic pinpoint landing system will be analyzed. This effort will allow CSDL the capability to perform rapid entry vehicle systems analysis and evaluate the design space spanned by vehicle characteristics and GNC to support its long-range technology requirements identification program.

PROBLEM

An integrated, multidisciplinary analysis framework that examines architecture, vehicle configuration, and vehicle GNC needs does not exist. However, future exploration needs could be rapidly identified and quantified with such a framework. In particular, efforts for the conceptual design of entry systems for robotic or manned Mars missions and Earth return missions will be enhanced by the framework. The ability to rapidly ascertain vehicle performance with GNC will enable the evaluation of potential technologies for each of these missions. This effort has direct application to several of CSDL's current space systems programs including the CEV and COTS programs and flight test efforts.

OBJECTIVES

The overall objective of this project is to deliver to CSDL a rapid entry system design and synthesis framework capable of providing an integrated assessment of vehicle configuration options, aerodynamics, aerothermodynamics, aerodynamic decelerator performance, mass estimation, hypersonic and terminal descent guidance, and navigation schemes on blunt bodies intended for planetary entry applications. In addition to conceptual design, such an integrated framework could be used to analyze the technologies necessary for pinpoint landing, or other mission architectures.

- Objective (1): Provide a rapid vehicle sizing and synthesis framework capable of analyzing vehicle geometry, hypersonic aerodynamics, aerothermodynamics, flight mechanics, GNC, deployable aerodynamic decelerator performance, thermal response, and mass requirements.

- Objective (2): Demonstrate the performance of the vehicle sizing and synthesis framework by analyzing two relevant test applications: an Orion-like skipping entry upon return from the moon and a future Mars robotic pinpoint landing system.

- Objective (3): Apply this integrated framework to refine the DFY07 assessment of the effects of various technologies on the ability to achieve a sub-100 m landed accuracy.

MILESTONE SCHEDULE

		Start	End
(1)	DFY08 Technical Plan/Year-End Report Submitted	5/15/07	
(2)	DFY08 UIR&D Contract Start	7/1/07	
(3)	Model and Tool Identification	7/1/07	9/15/07
(4)	Technical Interchange Meeting	9/15/07	
(5)	Definition of Parameters for Two Test Applications	8/31/07	10/15/07
(6)	CSDL Trajectory Analysis Integration	8/31/07	11/30/07
(7)	Hypersonic and Terminal Descent Guidance Integration	11/1/07	2/15/08
(8)	Midterm Review	12/15/07	
(9)	Delivery of Prototype Framework to CSDL	2/29/08	
(10)	Navigation Sensor and Filter Integration	2/15/08	4/1/08

(11)	Revisions on Prototype Framework Based on CSDL Feedback	3/15/08	5/15/08
(12)	Optimization Capability Inclusion	3/15/08	6/1/08
(13)	Monte Carlo Simulation Capability Inclusion	4/1/08	5/15/08
(14)	Second Prototype Framework Delivery to CSDL	6/1/08	
(15)	Revisions on Second Prototype Framework Based on CSDL Feedback	6/1/08	6/30/08
(16)	Delivery of Complete Framework, Final Report, and Final Review	6/30/08	
(17)	Contract End	6/30/08	

APPROACH

Sizing and Synthesis Framework

The basis of the integrated, multidisciplinary entry vehicle analysis framework is already in place based on FY07 development in the SSDL at the Georgia Institute of Technology. The framework will allow rapid conceptual entry and aeroassist vehicle analysis to be performed using vehicle geometry, aerodynamics, hypersonic trajectory, thermal response, terminal descent trajectory, and mass estimation models. The interaction of each of these modules is shown in Figure 1. The current framework has minimal provisions for GNC analysis and uses a simple three degree-of-freedom trajectory simulation. Upgrading this trajectory simulation capability to the CSDL EDL simulation and allowing for assessment of GNC algorithms and navigational sensors is the major emphasis of this DFY08 IR&D.

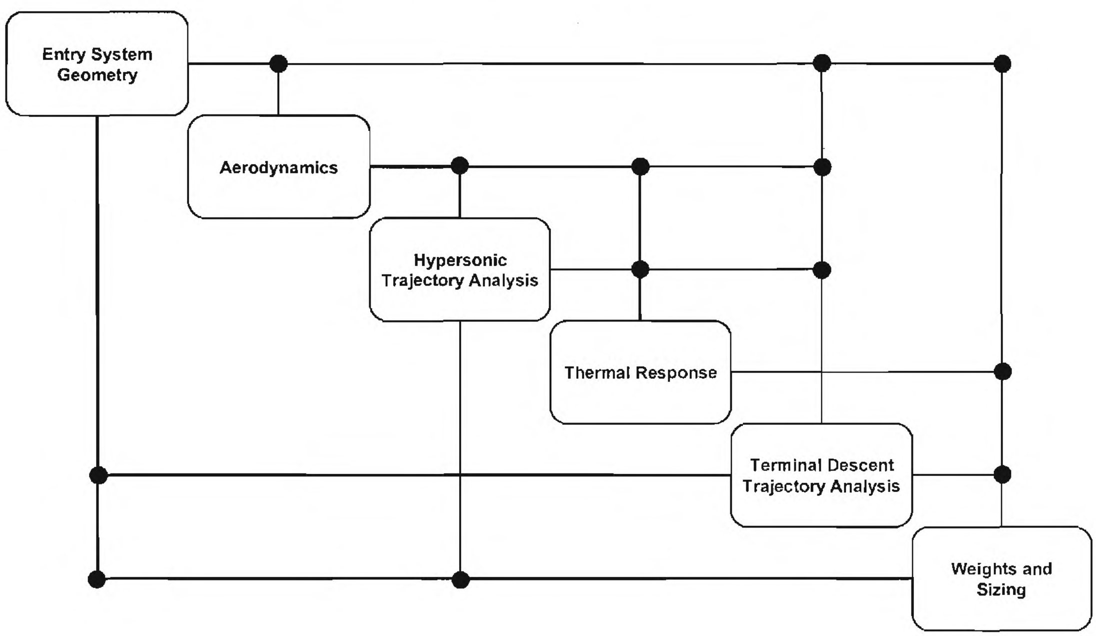

Figure 1. Design structure matrix for the interaction of framework models.

Planet Model

The framework will be generalized such that any planetary body with an atmosphere will be acceptable. As a baseline, the planet is assumed to be spherical with an exponential atmosphere and gravity varying with the inverse-square of distance from the center of the planet. However, the capability of including GRAM models will be included in the framework to allow for higher fidelity analysis at planet's where the GRAM models exist.

Entry Vehicle Geometry

Currently the framework has built in geometries for sphere-cone, biconic, and capsule shapes. For each of these shapes, the user has the option to scale and size the predefined shape by varying the parameters that define each shape. Additionally, an arbitrary shape can be imported from NASTRAN. From this geometric definition, a triangular mesh over the surface of each shape is created allowing for aerodynamic paneling methods to be applied.

Aerodynamics

Using the triangular surface mesh, modified Newtonian theory is assumed to generate hypersonic lift and drag coefficients as a function of angle of attack. A database of supersonic and subsonic aerodynamic decelerator aerodynamics is included for various configurations of parachutes, attached inflatable aerodynamic decelerators, and trailing aerodynamic decelerators.

Hypersonic Trajectory

The current framework provides for three degree-of-freedom numerical integration of the equations of motion with event triggers. As part of this development effort, this simulation capability will be replaced with CSDL's EDL simulator.

Currently, the trajectory module does not allow for a guidance capability. As part of this effort several algorithms which modulate the lift vector will be included. Included will be a version of the modified Apollo guidance planned for use by MSL and CEV. This capability will allow the entry vehicle shape to be evaluated along side with the guidance algorithm to examine the control authority exerted by the vehicle. Evaluation of a first-order predictor-corrector guidance algorithm will also be performed.

Thermal Response

Convective and radiative laminar heating correlations will be used to estimate the stagnation-point heat rate as well as the stagnation-point integrated heat load. Engineering approximations are included to model the heat rate at other points along the vehicle body. A database of thermal protection system (TPS) materials is included for evaluation of the required TPS thickness using a finite difference code accounting for surface ablation. The thermal response is coupled directly with the trajectory of the vehicle through the mass of the TPS and therefore iteration is necessary.

Terminal Descent Trajectory

The terminal descent portion of the framework will be developed as an extension of the DFY07 pinpoint landing UIR&D task in which subsonic, steerable aerodynamic decelerators as well as propulsive descent guidance algorithms were evaluated. For the steerable aerodynamic decelerator guidance algorithm, two classes of algorithms will be included, one which minimizes the end state energy as well as the miss distance from a target and another which minimizes the miss distance from a target as quickly as possible. Additionally, extensions beyond circular parachutes to parafoil shapes will be included to evaluate the benefit of such a device at various planetary bodies. In the case of propulsive terminal descent, the three guidance algorithms developed during the DFY07 UIR&D task will be included. These include an optimal gradient based algorithm, a modified version of the Apollo lunar module algorithm, and an analytic closed-form algorithm which is optimal provided aerodynamic forces are insignificant compared to gravitational and propulsive forces. Each of these algorithms has been shown to have advantages and disadvantages, particularly regarding computational complexity. Evaluating their effect within the system level design will give insight into the complexity of the guidance algorithm necessary to achieve a desired landed accuracy.

Navigational Models

Provisions within the framework will be made for integration of CSDL navigation sensor models. The inclusion of such models will allow for the assessment of the robustness of the design to navigational uncertainty and the impact this has on the desired landed accuracy[3].

Monte Carlo Simulation

Probabilistic assessment of the entry vehicle's performance will be enabled through Monte Carlo simulation capability. The present version of this entry systems analysis framework does not have this capability. User-defined dispersions will be allowed for the entry vehicle's state, characteristics, as well as atmosphere with normal and uniform distributions possible. Probability density functions and cumulative distribution functions will be generated and displayed to the user to assess the likelihood to meet a certain performance target. Real-Time Workshop (RTW), a Matlab product, will be used to convert the CSDL simulator into a stand-alone executable allowing for faster execution. The framework will have the ability to execute the Monte Carlo locally or in a cluster environment for more rapid evaluation. A schematic of the automated RTW and Monte Carlo environment is shown in Figure 2.

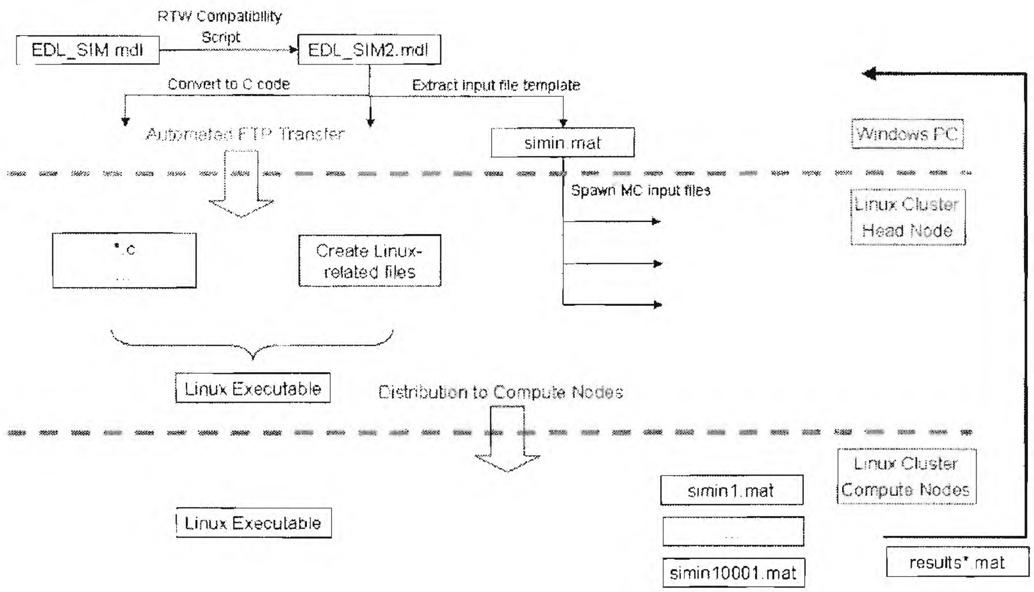

Figure 2. Real-Time Workshop and cluster environment.

Design Optimization

The integrated, multidisciplinary framework will permit the investigation and application of multidisciplinary design optimization methods to identify optimum with respect to a desired objective, such as minimum entry mass. Such methods, in conjunction with Monte Carlo analyses, may allow for robust entry configurations to be identified for specific missions. Additionally, trades in system level objectives may be easily visualized for various configurations by the automated generation of Pareto fronts, assuming the computational requirements can be minimized through efficient design space exploration algorithms.

PROGRESS

The DFY07 effort focused on identifying relevant technologies for achieving pinpoint landing accuracy (<100 m) for planetary landing applications, particularly at Mars. The performance of the system was evaluated for a Mars Science Laboratory (MSL) baseline architecture with use of CSDL's EDL simulator. Probabilistic assessments were performed on the effects of hypersonic guidance, guided subsonic aerodynamic decelerators, and propulsive terminal descent algorithms. Research was performed on an innovative EDL architecture—ballistic entry followed by a smart-divert capability that employs terminal descent guidance to reach one of several sites defined as safe *a priori* through orbital reconnaissance or some other means. In addition, significant modeling and run-time improvements were made to the CSDL EDL simulator – particularly for applications that require probabilistic assessment.

Simulator Development

To perform a probabilistic assessment of the technology trades associated with pinpoint landing a simulator capable of rapid Monte Carlo analysis was needed. The CSDL EDL simulator, obtained in DFY07, written in Simulink, allowed for Monte Carlo simulation.

However, the execution speed of the simulation prohibited a statistically significant number of cases to be analyzed. Because CSDL's simulator was written in Simulink, the opportunity existed to utilize RTW, a Matlab product that coverts Simulink code into a standalone C/C++ executable that runs approximately fifteen times faster. The relative speed improvement of RTW allowed a statistically significant Monte Carlo simulation to be conducted within reasonable computational time.

Most of Simulink and Matlab's functionality is maintained by RTW, although some functions of the CSDL simulator had to be modified to make them RTW compatible. For instance, RTW does not support structures for parameters that may vary after the executable is built, which forms the basis of the EDL simulator. Conversion of the simulator into RTW was handled by an automated script that converts the incompatible structure variables to RTW compatible variables, sets the appropriate RTW parameters for the execution build, and then builds the executable. This executable can then be run a multitude of times to generate results.

The baseline system design was derived from MSL with analyses performed for Mars. The MSL EDL system employs a Viking-heritage 70° sphere-cone aeroshell with a low lift-to-drag ratio whose aerodynamics were derived from CFD analysis by Langley, Viking-heritage supersonic parachute, and hypersonic guidance using a modified Apollo guidance algorithm.

To perform the probabilistic analyses, dispersions were taken from MSL data, including state, vehicle characteristics, as well as atmospheric dispersions. Unless otherwise noted, the dispersions shown in Table 1 were used for the vehicle's state and characteristics[5]. The MSL covariance used for state dispersions were taken from JPL data 10 minutes prior to entry assuming the fifth course correction maneuver was performed. These data were then propagated to atmospheric entry. Atmospheric variations were generated outside of the simulation using MarsGRAM 2005 with the dust opacity varying from 0.1 to 0.9. For the analyses performed over a majority of DFY07, perfect navigation knowledge is assumed. Work is currently underway to evaluate the effects of navigational uncertainty.

Table 1. Simulation parameters and dispersions.

	Parameter	***Nominal***	***Distribution***	***Deviation (3σ or min/max)***
State	Vehicle Entry Delivery Position Error	0 km	Gaussian	Based on MSL Covariance
	Vehicle Entry Delivery Velocity Error	0 m/s	Gaussian	Based on MSL Covariance
Vehicle	Entry Mass	2196 kg	Gaussian	2.0 kg
	Terminal Descent Engine Thrust	3047 N	Uniform	±5%
	Terminal Descent Engine Specific Impulse	210 s	Uniform	±0.67%
	Vehicle C_A Multiplier (Kn>0.1)	1	Gaussian	±5%
	Vehicle C_N Multiplier (Kn>0.1)	1	Gaussian	±10%
	Vehicle C_A Multiplier (M>10)	1	Gaussian	±3%
	Vehicle C_N Multiplier (M>10)	1	Gaussian	±5%
	Vehicle C_A Multiplier (0.8<M<5)	1	Gaussian	±10%
	Vehicle C_N Multiplier (0.8<M<5)	1	Gaussian	±8%
	Vehicle C_A Multiplier (M<0.8)	1	Uniform	±20%
	Vehicle C_N Increment (M<0.8)	0	Uniform	±0.03
	Parachute C_D Multiplier (M>1)	1	Uniform	±10%
	Parachute C_D Multiplier (M<1)	1	Uniform	±5%

Initialization

The baseline simulation was started at supersonic parachute deployment (M=2.0, h=8 km AGL). Positional state dispersions were taken from MSL data at parachute deployment assuming use of the modified Apollo guidance algorithm for hypersonic aeromaneuvering.

Propulsive Terminal Descent Guidance

In order to ensure fuel-optimal results, three different propulsive, terminal descent guidance algorithms were evaluated. A predictive guidance algorithm that utilizes a steepest descent method to ensure that a constrained local minimum is achieved, a modified Apollo lunar module guidance algorithm, and a closed-form optimal analytic guidance algorithm were each examined. Each algorithm was evaluated assuming the propulsive descent began at an altitude of 1.5 km.

The predictive algorithm ensures that a fuel-optimal solution is obtained; however, the algorithm requires successive iterations on the solution of differential equations to arrive at the control history and time-to-go at each call to the guidance function[2]. These iterations make the algorithm computationally expensive and relatively complex to implement. The algorithm was shown to be relatively robust to atmospheric, aerodynamic, propulsive, and state variations because the fuel-optimal control history can be updated as frequently as can be computationally afforded.

A modified Apollo lunar module guidance algorithm was also evaluated. While the algorithm does not guarantee fuel optimality, it does permit an analytic, closed-form solution for the time-to-go by assuming quadratic acceleration profiles laterally and a linear profile vertically[6]. The solution for the time-to-go is expressed in terms of either a linear or quadratic equation. Computationally this algorithm is the least demanding; however, use of this algorithm for pinpoint landing required significantly more propellant compared to the use of the other algorithms.

A closed-form optimal analytic guidance algorithm was also evaluated. While being slightly more computationally intensive relative to the modified Apollo lunar module guidance, it still permits a closed-form solution for time-to-go to be expressed in terms of a quartic equation while maintaining fuel-optimality provided the aerodynamic forces are significantly less than the propulsive and aerodynamic forces[4]. For the cases examined, this assumption held and little discernable effect in propellant mass fraction was seen at the 99% confidence level. The algorithm solves an unconstrained minimization problem. Increasing the weighting factor on the time-to-go was shown to ensure that the solution obtained did not descend beneath the planet's surface. Because this algorithm was shown to be computationally inexpensive with little discernable effect on fuel optimality, this algorithm was carried forward through the remainder of the DFY07 analyses.

The cumulative distribution functions for each of the three guidance algorithms is shown in Figure 3 while Table 2 shows a qualitative comparison of the performance of each of the algorithms with respect to various metrics.

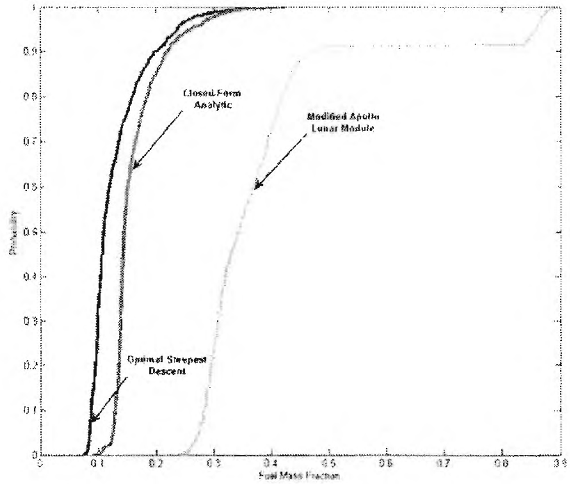

Figure 3. Guidance algorithm performance.

Table 2. Guidance algorithm comparison.

	Predictive Guidance	Modified Apollo Lunar Module	Closed-Form Analytic
Optimality	Good	Poor	Moderate
Computational Speed	Poor	Good	Good
Robustness	Good	Poor	Moderate
Ease of Implementation	Poor	Good	Good
Applicability to Flight	Moderate	Good	Good
Numerical Stability	Moderate	Moderate	Moderate

Carrying forward the analytic closed-form guidance law, work has also been performed to identify when to start the propulsive descent in terms of ballistic coefficient, velocity, downrange distance, altitude, and flight path angle. The propellant mass fraction required to accomplish a pinpoint landing has been tabulated against each of these parameters for future use within the guidance algorithm.

Subsonic Guided Parachute

The addition of a subsonic guided parachute was also evaluated for the MSL system. A circular parachute with four actuators was modeled and a guidance algorithm that minimizes the distance to the target as quickly as possible was implemented[7]. The subsonic parachute was deployed at Mach 0.9 and used until 1.0 km AGL. In this Mars application, the guided subsonic parachute showed marginal improvement relative to the no-chute solution (<3% at the 99% confidence level) as shown in Figure 4. This failure to improve performance significantly is due to the constrained timeline of Mars entry and its less dense atmosphere causing the useful time on the parachute to be insignificant. Two potential options exist for improving the performance of the parachute, using a parasail-like configuration or altering the guidance algorithm implemented to include energy in the merit function. These options will be explored in DFY08.

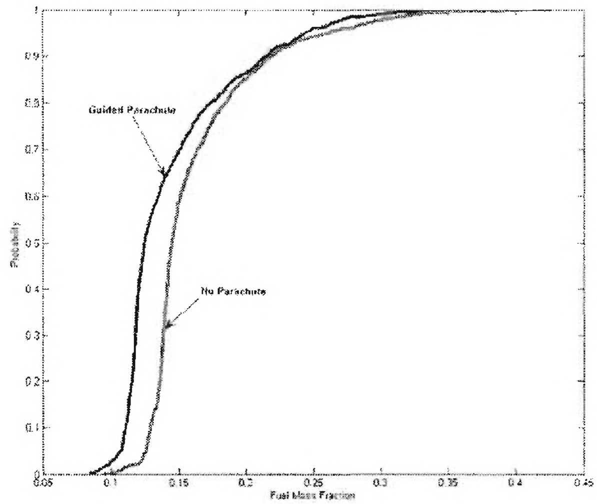

Figure 4. Guided subsonic parachute performance benefits.

Hypersonic Guidance

MSL currently implements a modified Apollo guidance algorithm for its hypersonic entry. This algorithm results in a three-sigma parachute deployment ellipse semi-major axis on the order of 10 km. Deterministically, varying the semi-major axis at parachute deployment between 0 and 20 km and evaluating the propellant mass fraction required to achieve a landed footprint of less than 100 m allows the influence of hypersonic guidance to be evaluated. This variation is shown in Figure 5. It is seen that the propellant mass fraction required is essentially constant for errors less than 3 km and mass fraction increases rapidly in a linear fashion beyond this downrange error. Thus, hypersonic guidance is an important consideration for pinpoint landing; however, based on this analysis, there is little reason to improve the guidance capability beyond 3 km.

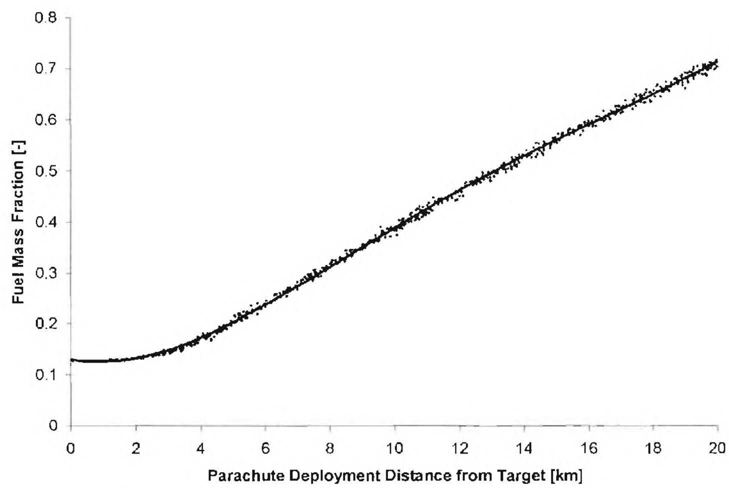

Figure 5. Impact of hypersonic guidance.

Smart Divert

Pinpoint landing facilitates a potentially lower cost EDL architecture to be studied that is applicable for robotic planetary exploration. This architecture uses a ballistic entry until supersonic parachute deployment and then evaluates the fuel expenditure required to land at one of several potential landing sites within the ballistic footprint that were established as safe prior to entry. The system autonomously selects the site which requires the least amount of fuel. This allows the cost and complexity of hypersonic aeromaneuvering to be eliminated while still affording safe landing at a scientifically interesting site.

Fixed Number of Landing Sites

An example case of Smart Divert may be visualized in Figure 6. Five sites were fixed in a cross pattern, and a Monte Carlo was conducted varying the parameters shown in Table 1. The dispersed trajectories may be seen in Figure 6 in which the vehicle flew to the fuel optimal site with no miss greater than 8 m (perfect navigation knowledge assumed). Work is underway to repeat this analysis with Phoenix landing site data where the landing site arrangement is based on the number of hazardous rocks within the region.

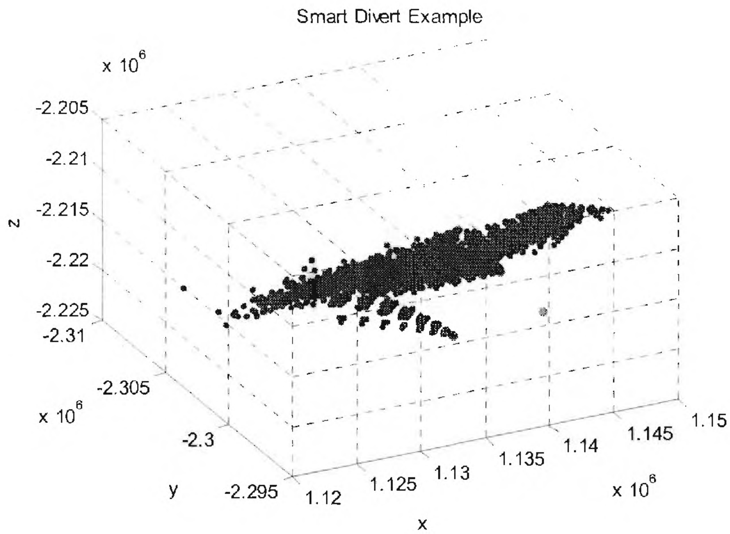

Figure 6. Smart divert trajectories.

Varying Number of Landing Sites

The effect of the number of designated landings sites for this architecture was evaluated by examining the fuel cost to achieve pinpoint accuracy in a ballistic ellipse compared to that in a rock field representative of that expected for the 2007 Mars mission, Phoenix. The number of landing sites within the ballistic ellipse known to be safe *a priori* was randomly selected from uniform distributions, ensuring that the entire ellipse is evaluated. Ten thousand case Monte Carlo simulations in which the landing site placement was the only parameter varied were conducted for one, two, three, and four sites. The results of this analysis are shown in Figure 7. It can be seen that as the number of sites increases, the pinpoint landing propellant mass required at the 99% confidence level decreases. A large reduction in propellant mass fraction occurs when the number of sites is increased from one to two. The reduction is less significant for each additional site and will eventually converge on the cost to perform a soft landing on the surface. Work is underway to repeat this analysis with Phoenix landing site data where the landing site arrangement is based on the number of hazardous rocks within the region (see Figure 8).

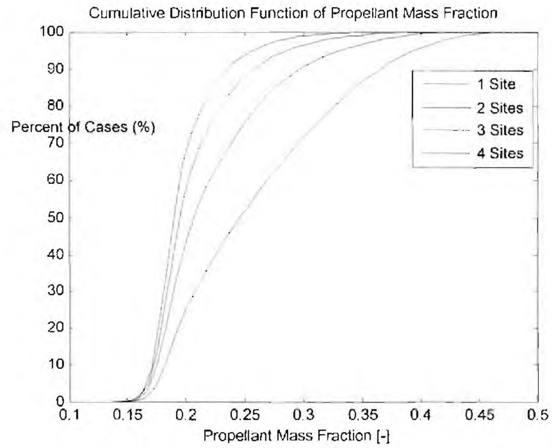

Figure 7. Smart divert benefits of increasing number of sites.

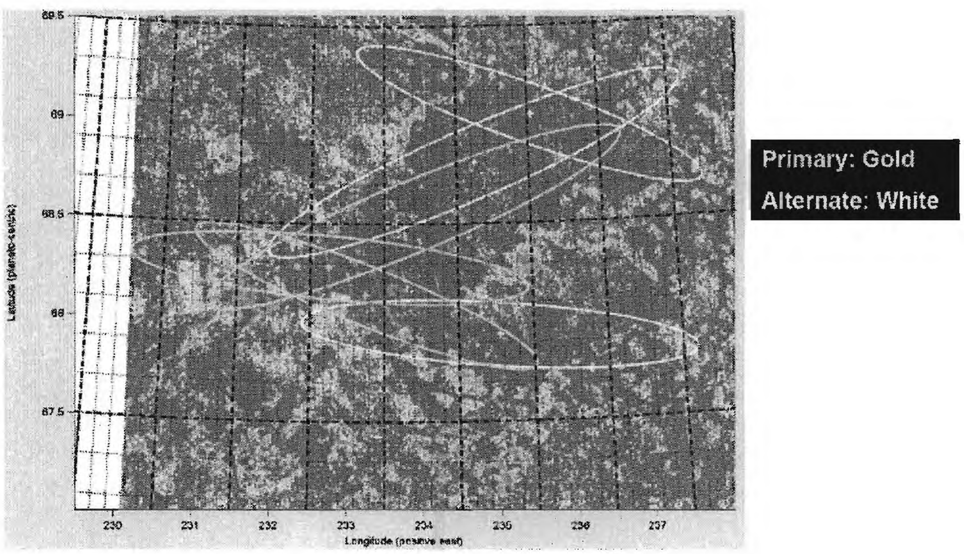

Figure 8. Phoenix rock field data and representative ballistic landing footprints (source: Doug Adams, JPL).

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RESUME

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Dr. Braun is an Associate Professor in the Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. As Director of Georgia Tech's Space Systems Design Laboratory, he leads a research program focused on the design of advanced flight systems and technologies for planetary exploration. He is responsible for undergraduate and graduate level instruction in the areas of space systems design, astrodynamics and planetary entry. Prior to coming to Georgia Tech, Dr. Braun worked at NASA Langley Research Center for sixteen years where he contributed to the design, development, test, and operation of several robotic space flight systems. Dr. Braun is an AIAA Fellow and the principle author or co-author of over 100 technical publications in the fields of planetary exploration, atmospheric entry, multidisciplinary design optimization, and systems engineering. He has previously worked with the Draper Laboratory technical staff on the NASA Concept Exploration and Refinement Study (2004-2005) and the ARES Mars Scout Airplane (2001-2003).

Michael Grant
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Mr. Grant is a graduate student in the Guggenheim School or Aerospace Engineering at the Georgia Institute of Technology. Mr. Grant earned a B.S. in Aeronautical and Astronautical Engineering from Purdue University in December 2005. As a cooperative education student, he has worked at the Johnson Space Center on MSL reference trajectory optimization by developing a multi-objective particle swarm optimizer that utilized POST. At Purdue University, he participated in a hybrid sounding rocket project and led the development of the trajectory simulation. Mr. Grant is a U.S. citizen.

Bradley Steinfeldt
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Mr. Steinfeldt is a second-year Master's student in the Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. Mr. Steinfeldt earned his B.S. in Aerospace Engineering from the University of Texas in August 2006. He has worked at the Jet Propulsion Laboratory in the EDL structures and configuration group working on design, analysis, and testing of mechanical devices and mechanisms. He has also led the GNC team of a university developed picosatellite through PDR and participated in NASA's Reduced Gravity Student Flight Opportunities Program. Mr. Steinfeldt is a U.S citizen.

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Mr. Matz is a fourth-year undergraduate student in the Guggenheim School of Aerospace Engineering at the Georgia Institute of Technology. Mr. Matz has worked at the Johnson Space Center in the Descent Analysis Group of the Flight Design and Dynamics Branch, where he worked on the design and analysis of the Crew Exploration Vehicle re-entry. Mr. Matz is a U.S. citizen.

Budgetary Plan for DFY08 UIR&D

1.	Planning and Supervision (12 months or as indicated)		
	(a) Principal Investigator	0.25 Man Months ____%	$ 3100
	(b) Research Assistants	24 Man Months ____%	$ 46000
	(c) Administration	____ Man Months ____%	$ 0
		Total Salaries and Wages:	$ 49100
2.	Employee Benefits (@ 23.5%)		$ 729
3.	Operating Expenses		
	(a) Materials & Services		$ 0
	(b) Travel (3 trips for 2 people to CSDL)		$ 4508
	(c) Graduate Student Tuition Remission		$ 12000
		Subtotal (Items 1 thru 3):	$ 66337
4.	Overhead (@ 54.6%)		$ 29663
5.	Capital Equipment		$ 0
6.	**Total Cost**		$ 96000